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# OPTIMIZING TRANSPORTATION OF DISASTER RELIEF MATERIAL TO SUPPORT U.S. PACIFIC COMMAND FOREIGN HUMANITARIAN ASSISTANCE OPERATIONS



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# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**OPTIMIZING TRANSPORTATION OF DISASTER  
RELIEF MATERIAL TO SUPPORT U.S. PACIFIC  
COMMAND FOREIGN HUMANITARIAN ASSISTANCE  
OPERATIONS**

by

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March 2013

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**OPTIMIZING TRANSPORTATION OF DISASTER RELIEF MATERIAL TO  
SUPPORT U.S. PACIFIC COMMAND FOREIGN HUMANITARIAN  
ASSISTANCE OPERATIONS**

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Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

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## **ABSTRACT**

In the wake of a global natural disaster, the U.S. Military often plays a significant logistical role at the request of the Department of State to overall relief efforts. Its primary purposes in these support missions are to safeguard lives, alleviate human suffering, and mitigate property damage. Our military has robust capabilities in transportation and security, and readily available stockpiles of life-saving humanitarian assistance and disaster relief material. Disaster relief operations are time-critical because delays in the delivery of aid can cause increased suffering and perhaps death. This thesis optimizes the transportation of humanitarian assistance and disaster relief material to the affected state within the U.S. Pacific Command Area of Responsibility. Optimization of this transportation network results in significant reductions of planning times, development and analysis of several alternative courses of action, and savings in delivery times and/or costs. A cost versus time analysis of various alternatives provides decision makers with more flexibility than they previously had.



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## **LIST OF ACRONYMS AND ABBREVIATIONS**

AMC	Air Mobility Command
AOR	Area of Responsibility
APOD	Aerial Port of Debarkation
APOE	Aerial Port of Embarkation
ATEM	Air Tasking and Efficiency Model
COA	Course of Action
DDC	Defense Distribution Center
DLA	Defense Logistics Agency
DoD	Department of Defense
DoS	Department of State
DR	Disaster Relief
DRAP	Disaster Relief Airlift Planner
FHA	Foreign Humanitarian Assistance
FLC	Fleet Logistics Center
GAMS	Generalized Algebraic Modeling System
HA	Humanitarian Assistance
HDR	Humanitarian Daily Ration
NGO	Non-government Organization
OFDA	Office of United States Foreign Disaster Assistance
QDR	Quadrennial Defense Review
USAID	United States Agency for International Development
USPACOM	United States Pacific Command
USTRANSCOM	United States Transportation Command



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## **EXECUTIVE SUMMARY**

When tasked by the Department of Defense, the U.S. military responds to global natural disasters and provides humanitarian assistance to affected states at the request of the State Department. The 2010 Quadrennial Defense Review discusses the need for the United States to succeed in a wide range of contingencies and specifically states that the Department of Defense must be prepared to provide the President with options to prevent human suffering due to large-scale natural disasters abroad.

The U.S. Pacific Command's (USPACOM) area of operation is home to nearly sixty percent of the world's population and experiences fifty percent of total world disasters. The region covers over 105 million square miles which can create logistics challenges even for routine military and non-military operations. When USPACOM executes foreign humanitarian assistance (FHA) operations in response to natural disasters, these operations are especially time-critical, and it is crucial to identify the logistic requirements as early as possible. The U.S. military has performed a number of FHA operations over the past few years; we know that we have the assets and resources to successfully deliver much needed aid. However, there still exists a need to develop better planning and resource allocation tools that quickly illuminate the logistics requirements at the outset of the operation in order to achieve efficiencies that result in decreased transportation times and costs.

We introduce the Disaster Relief Airlift Planner (DRAP), which is an optimization based decision support tool that determines the optimal routes to deliver material given certain data such as the disaster location and available airports, aircraft, and supply stockpiles. DRAP is formulated to minimize disaster material shortages while preferring to choose routes that reduce transportation costs (and delivery times) based on decision-maker constraints and priorities. It can also help determine the optimal aircraft allocation and positioning for an FHA operation, which can serve as a recommendation from USPACOM (as the supported command) to USTRANSCOM (as the supporting command).

DRAP can be used by logistics planners and decision makers to conduct tradeoff analysis among routes with respect to transportation costs and demand shortages in very short time horizon logistics planning. It can save considerable time in the early and crucial stages of a disaster relief effort. This can greatly contribute to the primary purposes of the U.S Military conducting an FHA operation of safeguarding lives, alleviating human suffering and mitigating great property damage.

## **ACKNOWLEDGMENTS**

The author would like to acknowledge the assistance and support provided by U.S. Pacific Command in making the Disaster Relief Airlift Planner a tool that has a direct military application and one that benefits our military in our ongoing efforts to promote peace and stability in the world. In particular, I would like to thank LCDR Dan Bessman, both for providing this thesis topic and for his role as liaison to the sponsor.

Special thanks to Professor Carlyle for his guidance and assistance in writing this thesis and developing the decision support tool. He is a true master of his craft and it was a privilege to work with him. Thanks to CDR DeGrange for his advice and recommendations as a second reader and also for his mentorship as a senior supply officer.

I especially wish to thank my wife, Christa, whose love and support have no bounds. To my children, Liam, Luke, and Addison, who inspire me to be a better father and a better officer. To my father, Boris, who has always guided me with good advice and to my brother, Simon, the most studious person I know.

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## **I. INTRODUCTION**

### **A. PROBLEM STATEMENT**

When tasked by the Department of Defense, the U.S. military responds to global natural disasters and provides humanitarian assistance to affected states at the request of the State Department. The 2010 Quadrennial Defense Review discusses the need for the United States to succeed in a wide range of contingencies and specifically states that the Department of Defense must be prepared to provide the President with options to prevent human suffering due to large-scale natural disasters abroad.

The U.S. Pacific Command's (USPACOM) area of operation (AOR) is home to nearly sixty percent of the world's population and experiences fifty percent of total world disasters (USPACOM 2013). The region covers over 105 million square miles which can create logistics challenges even for routine military and non-military operations. When USPACOM executes foreign humanitarian assistance (FHA) operations in response to natural disasters, these operations are especially time-critical, and we need to understand and address the logistic requirements as early as possible. The U.S. military has performed a number of FHA operations over the past few years; we know that we have the assets and resources to rapidly and successfully deliver much needed aid. However, there still exists a need to develop better planning and resource allocation tools that quickly illuminate the logistics requirements at the outset of the operation in order to achieve efficiencies that result in decreased transportation times and costs. To quote Romano (2011):

In the past several years, the Department of Defense (DOD) has increasingly participated in complex relief operations with other U.S. Government agencies and nongovernmental organizations in response to humanitarian crises. These operations pose significant challenges for military logisticians. Most humanitarian assistance/disaster relief (HA/DR) operations are characterized by rapidly changing circumstances and a lack of clear and accurate information; they are also distinguished by substantial pressure to quickly provide relief supplies and materiel to an affected area. While DOD has the airlift capacity, disaster funding, critical supplies, and logistics systems to be an effective interagency partner in responding to these crises, additional efforts are needed to provide military

logisticians with the appropriate capabilities, tools, and training to meet the varied challenges associated with complex HA/DR operations.

## **B. BACKGROUND**

### **1. U.S. Military Role in FHA**

With the exception of immediate response to prevent loss of life, military forces normally conduct FHA only upon the request of the Department of State (DoS) and in coordination with the chief of mission and United States Agency for International Development (USAID). The military normally plays a supporting role in FHA. Typical supporting roles include: providing prompt aid that can be used to alleviate the suffering of foreign disaster victims, transferring on-hand DoD stocks to respond to unforeseen emergencies, and providing funded and space available transportation of humanitarian and relief supplies. Department of Defense Joint Publication 3–29 Foreign Humanitarian Assistance (2009) outlines DoD’s unique assets for effective response and can play a key role in foreign humanitarian crises, for example:

- The U.S. military possesses exceptional operational reach that can be employed to enhance an initial response.
- The U.S. military augments private sector capability and thus limits threats to regional stability.
- The U.S. military’s unmatched capabilities in logistics, command and control (C2), communications, and mobility are able to provide rapid and robust response to dynamic and evolving situations among vastly different military, civilian, and government entities.

#### ***a. Types of FHA Mission***

Department of Defense Joint Publication 3–29 Foreign Humanitarian Assistance (2009) lists the following common foreign humanitarian assistance missions:

- 1) Relief missions. Relief missions include prompt aid that can be used to alleviate the suffering of disaster victims. Potential relief roles for U.S. forces include immediate response to prevent loss of life and destruction of property, construction of basic sanitation facilities and shelters, and provision of food and medical care.
- 2) Dislocated civilian support missions. Dislocated civilian support missions are specifically designed to support the assistance and protection for dislocated civilians. Support missions may include camp organization

(basic construction and administration); provision of care (food, supplies, medical attention, and protection); and placement (movement or relocation to other countries, camps, and locations).

3) Security missions. Security missions may include establishing and maintaining conditions for the provision of FHA by organizations of the world relief community. In some cases, the affected country will not be able to meet the required conditions and may request assistance from U.S. military forces to secure areas for storage of relief material until it can be distributed to the affected population. Other tasks may involve providing protection and armed escorts for convoys and personnel delivering emergency aid, protection of shelters for dislocated civilians, and security for multinational forces, nongovernmental organizations (NGOs), and intergovernmental organizations (IGOs).

Rapid delivery of HA/DR material is crucial to the success of all three types of missions. Without the timely and consistent delivery of food, shelter, security, and medical commodities, these missions are unsustainable and situations “on the ground” rapidly deteriorate. The importance of logistics planning in FHA operations cannot be overstated.

## **2. USPACOM’s Role in Foreign Disaster Relief**

Figure 1 is a diagram representing coordination at the joint task force level. The Chief of Mission is the DoS’s on-scene representative and is the lead authority for the disaster relief efforts. The geographic combatant commander is in a supporting role to the chief of mission and typically establishes a Crisis Action Team, a Joint Task Force, and a Civil Military Operations Center in order to coordinate efforts by joint military, interagency, civilian, affected state, and any other parties participating in the relief effort. USPACOM is one of six geographic combatant commanders. Joint Publication 3–29, Foreign Humanitarian Assistance (2009) provides in depth explanations of the roles of all entities involved in FHA operations.



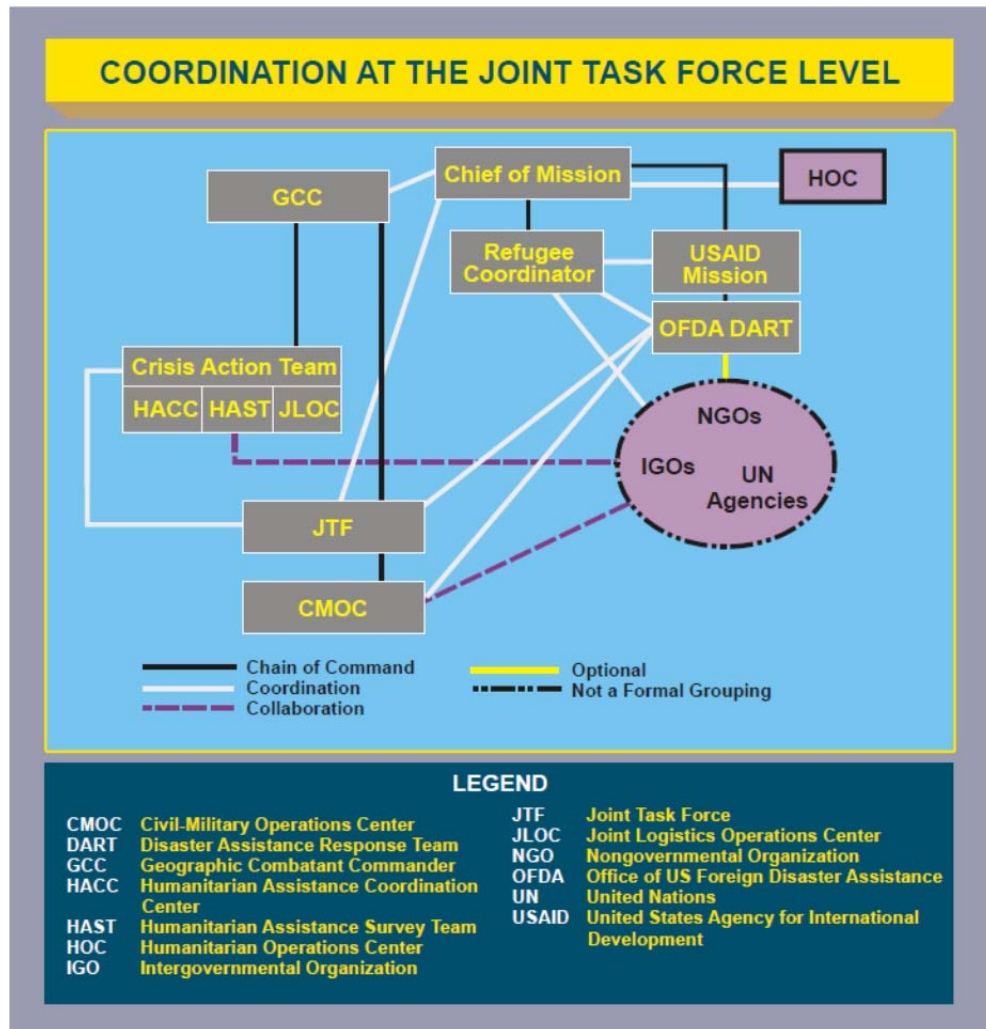


Figure 1. Coordination at the Joint Task Force Level (From DoD 2009)

### 3. Elements of Foreign Disaster Relief

Foreign Disaster Relief is provided in response to foreign disasters caused by the commonly used terms “Acts of God” and “Acts of man” as shown in Figure 2. A more detailed description of disaster types is given in Chapter II. As previously stated, when the DoS makes a determination that these disasters are of a degree that foreign disaster relief shall be provided, DoD and its components are tasked to support DoS and provide the Affected State with a variety of Humanitarian Services, Supplies, and Transportation. Broad categories of aid include shelter, subsistence, and medicine. This work deals the transportation of HA/DR commodities that fall within all of these categories.

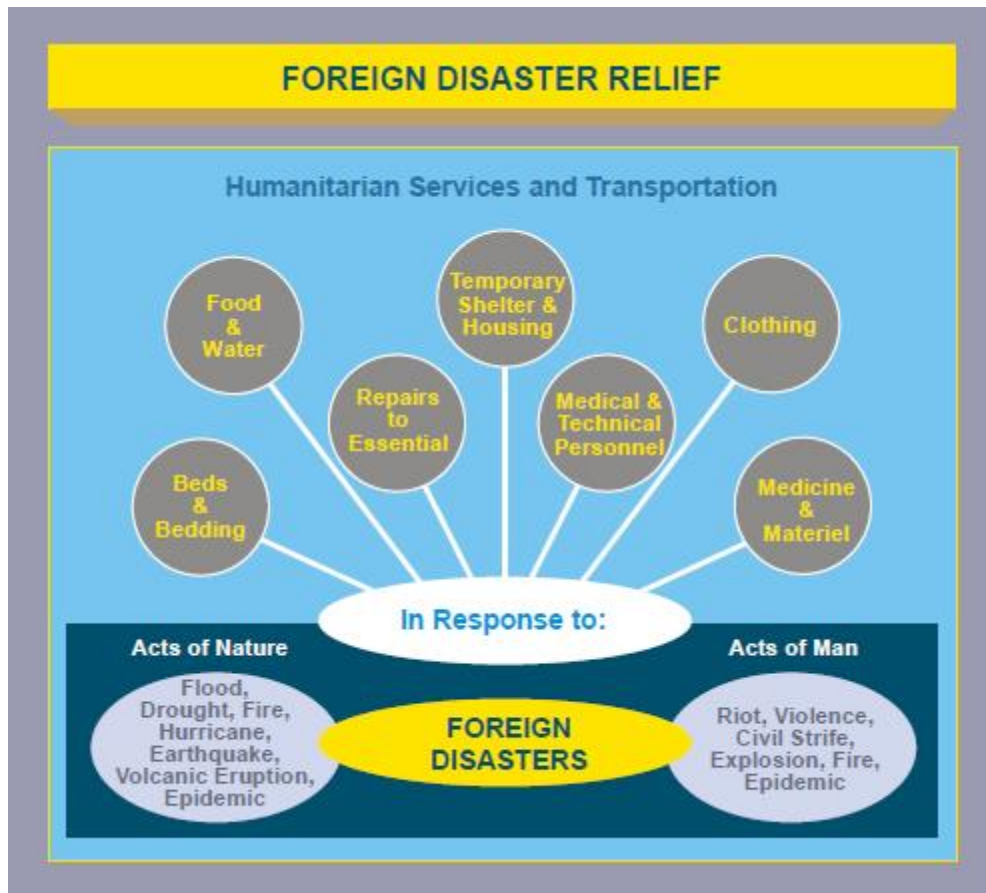


Figure 2. Foreign Disaster Relief (From DoD 2009)

### C. HISTORICAL PERSPECTIVE FOR USPACOM AOR

The USPACOM AOR encompasses about half the earth's surface, stretching from the waters off the west coast of the U.S. to the western border of India, and from Antarctica to the North Pole (see Figure 3). There are few regions as culturally, socially, economically, and geo-politically diverse as the Asia-Pacific. The 36 nations that comprise the Asia-Pacific region are home to more than 50% of the world's population, three thousand different languages, several of the world's largest militaries, and five nations allied with the U.S. through mutual defense treaties. Two of the three largest economies are located in the Asia-Pacific along with ten of the fourteen smallest. The AOR includes the most populous nation in the world, the largest democracy, and the

largest Muslim-majority nation. More than one third of Asia-Pacific nations are smaller, island nations that include the smallest republic in the world and the smallest nation in Asia. (USPACOM 2013)



Figure 3. USPACOM Area of Responsibility (From USPACOM, 2013)

USPACOM has participated in more than 15 disaster relief operations in 12 countries and one U.S. territory (Japan, South Korea, the Philippines, Palau, Indonesia, Thailand, Vietnam, Laos, Burma, India, Madagascar, Sri Lanka and Guam) since 1998. Figure 6 shows the location and type of major disasters of USPACOM foreign disaster response from 2008–2011. As stated by Miles (2012):

The Asia-Pacific region experiences more natural disasters than any other part of the globe. It sits squarely on the earthquake-prone “Ring of Fire” and also suffers frequent cyclones, hurricanes or typhoons, floods, and even volcanic eruptions.

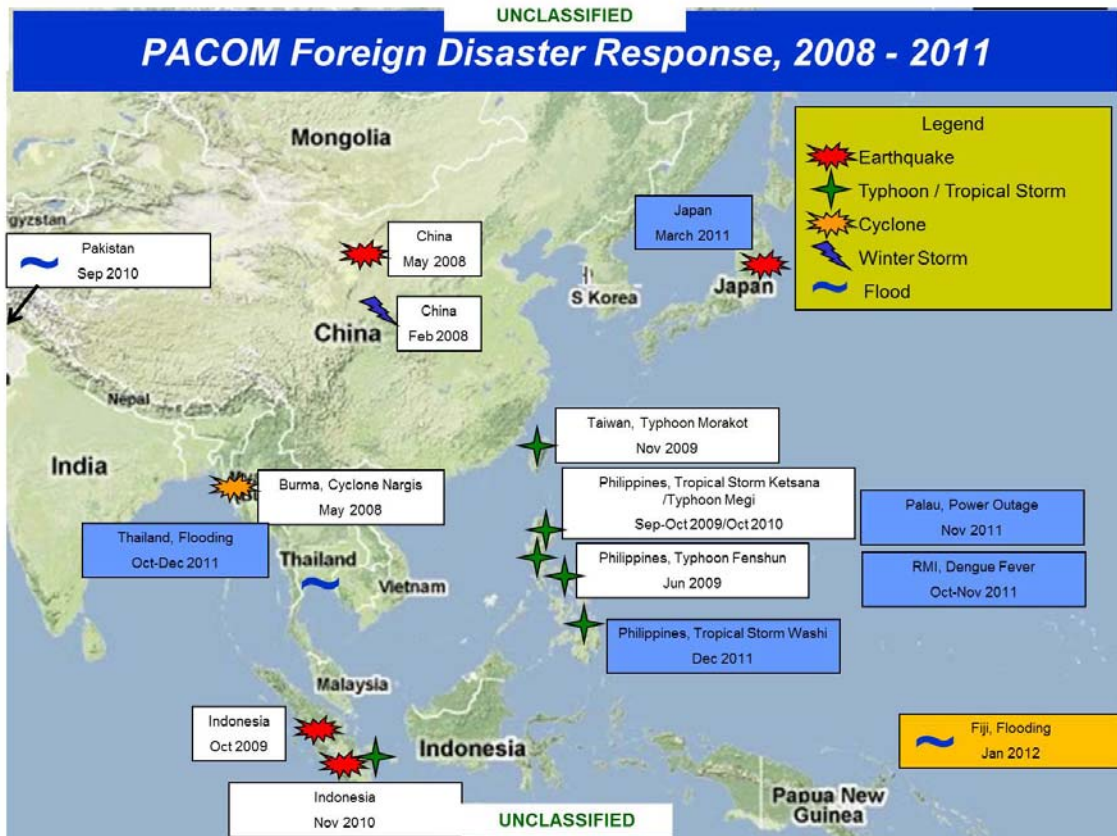


Figure 4. USPACOM Foreign Disaster Response, 2008 – 2011  
(From USPACOM 2012)

#### D. DISASTER CLASSIFICATION

According to the United Nations International Strategy for Disaster Reduction (UN ISDR 2006), a disaster is defined to be an unforeseen and often sudden event that causes great damage, destruction and human suffering that overwhelms local capacity, necessitating a request to the national or international level for external assistance. Disasters can be separated into two major categories: “acts of God” (or natural disasters) and “acts of man” (also known as technological disasters). Natural disasters can be further split into three groups:

- Hydro-meteorological disasters include floods and wave surges, storms, droughts and related disasters (extreme temperatures and forest/scrub fires), landslides and avalanches.

- Geophysical disasters include earthquakes, tsunamis and volcanic eruptions.
- Biological disasters include epidemics and insect infestations.

Manmade, or Technological disasters are events that brings on a major crisis, causes massive loss of life and property and may endanger the environment in which it occurs. Technological disasters include industrial accidents (chemical spills, gas leaks, and radiation), transport accidents and other miscellaneous accidents such as explosions and fires that are not caused by nature. An example of a technological disaster is the 1986 Chernobyl nuclear reactor explosion.

## **E. SCOPE OF STUDY**

The aim of this work is to facilitate the logistics planning and decision making process of transporting HA/DR material to states affected by a natural disaster. We have developed the Disaster Relief Airlift Planner (DRAP), an optimally based decision support tool, to automate the current manual process of deciding which air routes to fly, which types and how many of each type of available aircraft to use, and which sources of supply to draw from. These and a multitude of other questions arise during the outset of every FHA operation. The current manual process often results in only one course of action (COA) provided to the decision maker. In addition, as good as the logistics planners may be, it is unlikely that the single COA they develop is the optimal one. A manual planning process also has difficulty in foreseeing when and where the shortages will occur beforehand. Lastly, the manual process takes hours, sometimes days, time which is crucial in the early stages of the disaster relief effort. Our aim is to reduce the planning horizon from days and hours to hours and minutes. We also seek to minimize HA/DR commodity shortfalls delivered to the affected state while keeping transportation costs as low as possible.

Figure 5 is a snapshot that shows Defense Logistics Agency (DLA) depot locations. These are the main (but not only) sources of military supply of HA/DR commodities available for USPACOM FHA operations. When a disaster occurs and DoD is tasked to respond, the J4 (“Logistics”) cell of the joint staff provides the J3



(“Operations”) cell with potential nodes in the affected country and the quantities & locations of HA/DR stocks (managed by several agencies and entities) throughout the AOR. The J3 selects the mode of transportation (usually an airframe), the Aerial Port of Embarkation (APOE), the quantity of HA/DR material, and the Aerial Port of Debarkation (APOD). Our goal is to provide a decision support tool that can give the planners and the decision maker several COA’s that can be varied by airframe type and number, selection of airports, and selection and prioritization of HA/DR commodities. DRAP calculates costs of flying a particular route by fuel consumption and operations costs (per hour) of a particular airframe. It uses these costs to optimize route selection while minimizing demand shortages.

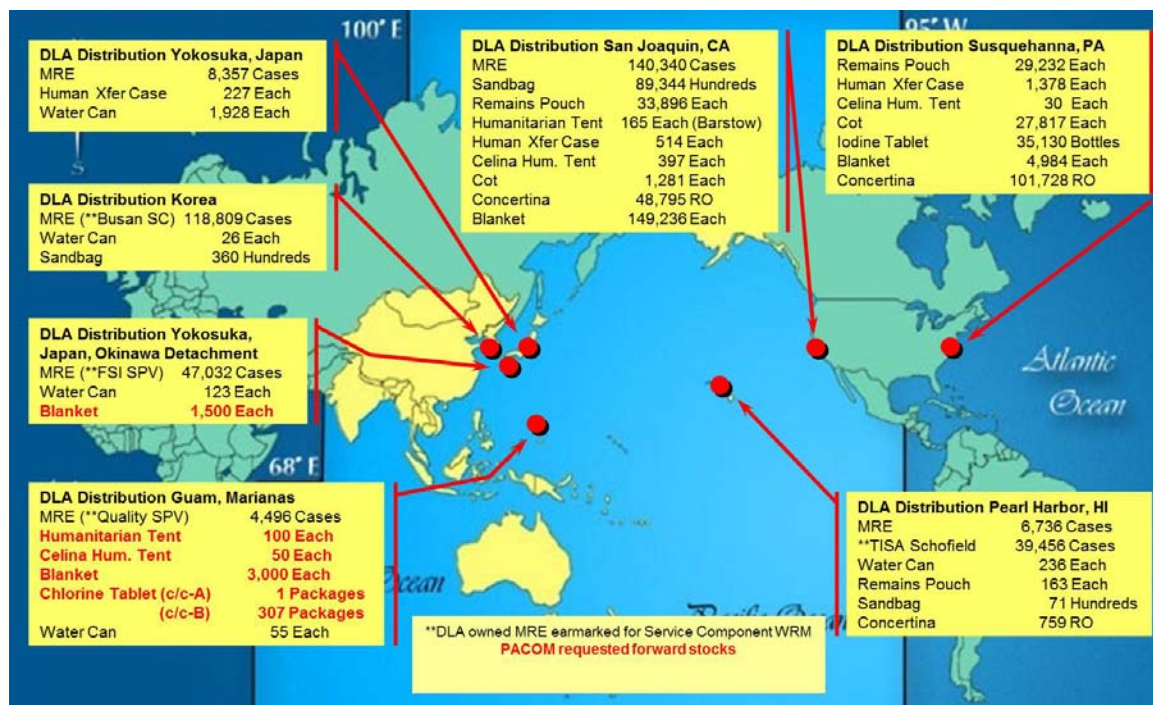


Figure 5. Positioning of Humanitarian Assistance and Disaster Relief material available to USPACOM (From USPACOM 2012)

## 1. Literature Review

McCall (2006) builds models that help design hot and cold pack-up kits and then optimally preposition them to respond more rapidly to any crisis in the USPACOM AOR based on the weather factors in the environment. At the time of this work, USPACOM

continues to transport commodities individually as required and not as pack-up kits and so we choose to focus on the current operating procedures. Dozier (2012) examines humanitarian assistance cargo transportation. That thesis, however, deals with humanitarian assistance as a goodwill tool to enhance strategic objectives in the EUCOM AOR through optimization of a transportation network. This thesis considers logistics issues associated with disaster relief operations, which require high volumes of material to be delivered in very short time frames.

Ferguson and Danzig (1954) describe a linear programming model which assigns aircraft of different types and operating costs to a given set of nonstop routes, ensuring that sufficient seating capacity is supplied, and that aircraft are available. Baker et al. (2002) make the distinction between commercial and military optimization problems, and build a model that moves equipment and personnel using aircraft with differing characteristics through a transportation network using Time-Phased Force Deployment Data.

Brown et al. (2013) describe a military airlift planning tool, The Air Tasking and Efficiency Model (ATEM), which is the basis for our Disaster Relief Airlift Planner (DRAP). ATEM plans routes and aircraft configurations (capacity of passenger seats and pallet positions) for a heterogeneous fleet of aircraft flying between multiple airfields. ATEM respects limits on crew duty periods, times and abilities of each airfield to handle and fuel each aircraft type, and aircraft speed and carrying capacity (Brown et al. 2013).

ATEM is an operational to tactical level decision support tool used to optimize intra-theatre airlift, while DRAP is an inter-theatre and intra-theatre airlift planner that aids decision making and planning on the operational level and does not at present time detail down to the tactical level. Also, ATEM accounts for capacity by passenger seats and pallet positions whereas DRAP models capacity by volume and weight of HA/DR commodities.

Wray (2009) simplifies a complex helicopter routing scheduling planning cycle through use of an Excel-based program called the Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT). DRAP, like MASHPAT creates all allowable

routes for an aircraft type to fly based on time and landing zone restrictions. However, MASHPAT considers rotary wing aircraft flying relatively short distances in a hostile environment while DRAP assesses fixed wing aircraft flying long distances in a permissive environment.

## **2. Assumptions**

Our research on optimizing the transportation of humanitarian assistance and disaster relief has some direct parallels to McCall (2006). Specifically, the environment in which FHA operations are conducted and the nature of the DoD response are much the same. We therefore adopt two assumptions from that work with some modifications.

### ***a. The Mission is Short-term in Scope***

The aim of this work is to provide rapid support to a disaster relief effort by transporting high volumes of readily available sources of relief materials to meet the already identified requirements of the affected state. The mission is short-term in scope and will end when relieved by other NGOs and agencies. Slow-onset disasters, such as drought, are more likely to have a long-term impact on a population's nutritional status. Relief operations in these regions tend to be longer term efforts and organizations have ample time to plan the operation. NGOs have the expertise required to operate in these areas and any U.S. military presence would likely be for peacekeeping missions rather than humanitarian assistance, so they are not studied in this thesis.

### ***b. The Model Assumes a Permissive Environment***

According to the Chief of Naval Operations Naval Warfare Publication (NWP) 3-07, Naval Doctrine for Military Operations Other Than War (1998), a permissive environment contains little or no opposition or resistance to the relief operations. A permissive environment generally exists for pure relief efforts after a natural disaster where the host nation's control of the nation is not threatened. Characteristics of a permissive environment include minimal security requirements, clear objectives, host nation cooperation, participation of Non-government Organizations (NGOs) and commonality of purpose for all parties. Relief operations in which naval



forces operate in uncertain or hostile environments will have additional force protection and rules of engagement considerations. The decision support tool developed in this work can be modified to allow the user to insert some of these considerations, for example a “no-fly” zone over certain countries, but overall the model assumes a permissive environment.

We provide the formulation of the HA/DR Transportation Model and show how it fits into the DRAP decision support tool in Chapter II of this thesis, and we analyze two scenarios in Chapter III, highlighting the speed of the solution, the quality of the solution, and alternate courses of action in each scenario.

## II. THE DISASTER RELIEF AIRLIFT PLANNER

We present an integer linear program formulation of the HA/DR Transportation Model which underlies DRAP. The nodes  $n \in N$  in our transportation network model are international and military airports in the USPACOM AOR. They may serve as supply nodes, transshipment nodes, or disaster (or demand) nodes  $d \in D \subseteq N$ . Each commodity type  $c \in C$  is identified by an abbreviation of the actual material names, and has data associated with it such as unit of issue, weight, volume, and for each node, supplies (– demands) of that commodity at that node. Weight is given in pounds while volume is represented as a fraction of the maximum volume allowable on a 463L standard pallet.

Aircraft types  $a \in A$  have associated data designating payload, volume capacity, fuel capacity, fuel consumption in gallons per mile, operating cost in dollars per hour, and range for each aircraft in nautical miles.

A set of air routes  $r \in R$  is given to the HA/DR transportation model. In our model, each route consists of a sequence of airports, an associated aircraft type, a capacity for that route in pallets (based on aircraft type), and a capacity in pounds based on the length of the longest leg (i.e., pair of sequential airports) in the route in nautical miles.

### 1. Sets and Indices [cardinality]

$n \in N$	transportation network nodes, i.e., airports (alias $i, j, d$ ) [~50]
$d \in D \subseteq N$	disaster nodes, i.e., airports with demands [~10]
$c \in C$	commodity types [16]
$a \in A$	aircraft types (C-5, C-17, C-130) [3]
$r \in R$	air routes [~1000]
$n \in S_r$	starting node $n$ of route $r$
$n \in N_r$	nodes $n$ on route $r$
$a \in A_r$	aircraft $a$ that can fly route $r$

### 2. Parameters [units]

$cost_r$	cost to fly route $r$ [\$]
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$cap_r$	volume capacity of aircraft route $r$ [pallets]
$payload_r$	weight capacity of aircraft route $r$ [pounds]
$duration_r$	duration of flight of route $r$ (by aircraft $a$ ) [hours]
$downtime_r$	minimum hours between flights on route $r$ (of aircraft $a$ aggregated for refuel and onload or offload) [hours]
$b_{c,n}$	supply ( – demand) of commodity $c$ at node $n$
$pen_{c,j}$	shortage penalty of commodity $c$ at disaster node $j$ [\$ per unit short]
$base_{a,n}$	number of aircraft of type $a$ based at node $n$
$wt_c$	shipping weight of commodity $c$ [pounds/unit]
$vol_c$	shipping volume of commodity $c$ [fraction of a pallet/unit]

### 3. Scalars [units]

$fuelcost$	aviation fuel cost[\$/gal]
$horizon$	hours in planning horizon [integer]

### 4. Positive Variables [units]

$SHORTAGE_{c,j}$	unmet demand of commodity $c$ at node $j$ [pounds]
$PICKUP_{c,i,r}$	amount of commodity $c$ picked up from node $i$ on route $r$ [pounds]
$DROPOFF_{c,j,r}$	amount of commodity $c$ dropped off at node $j$ on route $r$ [pounds]

### 5. Integer Variables [units]

$X_r$	number of aircraft of type $a$ flying route $r$ [integer]
-------	---

## 6. Formulation

$$\begin{aligned} \text{MIN}_{X, \text{SHORTAGE}} \quad & \sum_r \text{cost}_r X_r + \sum_{\substack{c \in C, \\ j \in D}} \text{pen}_{c,j} \text{SHORTAGE}_{c,j} \end{aligned} \quad (1)$$

$$\sum_{i \in N_r \setminus D} \text{PICKUP}_{c,i,r} = \sum_{j \in N_r \cap D} \text{DROPOFF}_{c,j,r} \quad \forall c \in C, r \in R \quad (2)$$

$$\sum_{c \in C, i \in N_r \setminus D} \text{vol}_c \text{PICKUP}_{c,i,r} \leq \text{cap}_r X_r \quad \forall r \in R \quad (3)$$

$$\sum_{c \in C, i \in N_r \setminus D} \text{wt}_c \text{PICKUP}_{c,i,r} \leq \text{payload}_r X_r \quad \forall r \in R \quad (4)$$

$$\sum_{\substack{r: a \in A_r, \\ i \in S_r}} (\text{duration}_r + \text{downtime}_r) X_r \leq \text{horizon} * \text{base}_{a,i} \quad \forall a \in A, \forall i \in N \quad (5)$$

$$\sum_{r: i \in N_r} \text{PICKUP}_{c,i,r} \leq b_{c,i} \quad c \in C, \forall i \in N \setminus D \quad (6a)$$

$$\sum_{r: j \in N_r} \text{DROPOFF}_{c,j,r} + \text{SHORTAGE}_{c,j} \geq -b_{c,j} \quad c \in C, \forall j \in D \quad (6b)$$

$$\begin{aligned} X_r &\geq 0 \text{ integer} & \forall r \in R \\ \text{PICKUP}_{c,i,r} &\geq 0 & \forall c \in C, \forall i \in N \setminus D, r \in R \\ \text{DROPOFF}_{c,j,r} &\geq 0 & \forall c \in C, \forall j \in D, r \in R \\ \text{SHORTAGE}_{c,j} &\geq 0 & \forall c \in C, \forall j \in D \end{aligned} \quad (7)$$

## 7. Discussion

The objective function (1) minimizes both the number of routes used to deliver the disaster relief cargo in terms of cost to fly each route and the shortages of material at each of the disaster nodes. For all commodities and all routes, constraint (2) ensures the amount of cargo dropped off is equal to the amount of cargo picked-up. For all routes, constraint (3) ensures the sum of cargo picked up by a given plane on a given route does not exceed the volume capacity of that type of aircraft. For all routes, constraint (4) ensures the sum of cargo picked up by a given plane on a given route does not exceed the weight capacity of that type of aircraft. For all nodes and all aircraft types, constraint (5) limits the number of routes selected to the number of airplanes available at the bases while accounting for flight duration and aircraft downtimes in a given time horizon. For each commodity at a supply node, constraint (6a) ensures that the quantities loaded do not exceed the given supply data. For each commodity required at a disaster node,

constraint (6b) ensures that every unit of demand is either met with a dropoff or accounted for as a shortage. Constraints (7) define decision variable domains.

## **B. DISASTER RELIEF AIRLIFT PLANNER MODEL**

### **1. Transportation Network**

We develop our transportation network in the USPACOM AOR using international and military airports as nodes. DRAP uses the geo-location of the airports to calculate great circle distances of the routes. These distances can be replaced by other values if, for example, certain routes must divert due to “no-fly” zones. DRAP is user-friendly and adding airports to the tool requires only the airport’s name, latitude and longitude, and an indication of what types of aircraft can land there. The model identifies certain nodes as supply nodes and disaster nodes. Supply nodes are sources from which HA/DR material can be obtained while disaster nodes have a demand for these commodities. The arcs in the networks are air routes that connect one node (or airport) to another.

### **2. Route Enumeration**

DRAP uses a stack-based enumeration algorithm that conducts a depth first search. The algorithm in DRAP is a modification of the route generation algorithm in the Air Tasking and Efficiency Model (ATEM) created by Brown et al. (2013). Both ATEM and DRAP plan routes for a heterogeneous fleet of aircraft flying between multiple airports.

The DRAP algorithm takes an aircraft type and a starting location that has aircraft of that type and enumerates all valid routes from supply nodes through transshipment nodes to demand nodes. A route is defined as “valid” when the longest distance between two nodes on the route is equal to or less than maximum range of the aircraft trying to fly that route. The enumeration adds successive airports to a current route, extending it by one “stop” at a time, as long as a few specific conditions are met:

- 1) the aircraft must be able to make the flight between the last airport on the current route and the new airport;
- 2) the aircraft must be able to land at the new airport;

- 3) the total flight time of the route must not exceed the maximum utilization hours for the aircraft;
- 4) a route cannot involve more than a given maximum number of stops; and
- 5) once a route contains a demand node, it cannot visit any more supply nodes on this route (i.e., routes start with pick-ups and end with drop-offs).

If any of these rules is violated, the algorithm backtracks and looks for a different airport to add to the route. Once all possible extensions have been considered, the algorithm backtracks, and this process continues until the start node is removed.

Each aircraft's load capacity is determined as a linear function of its range. DRAP associates six range levels (from 0% to 100% in increments of 20%) for each aircraft and connects it with a payload. We obtain valid and well established data points from open Internet sources including "Factsheets" provided by the U.S. Air Force (USAF 2013). At a minimum, we obtain ranges for each airframe used at empty and full payload capacities, and at least one range data point in between. We determine a linear regression equation and extrapolate range levels required to obtain the six levels previously described. A comparison of Figure 6 with Figure 7 shows us that the assumed linear relationship is acceptable for the purposes of this model.

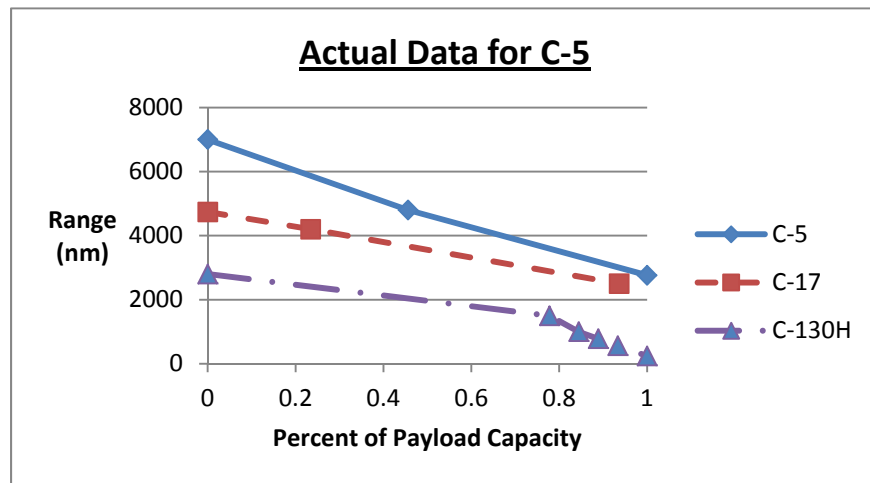


Figure 6. Payload capacity and range for C-5 airframe (From USAF 2013)

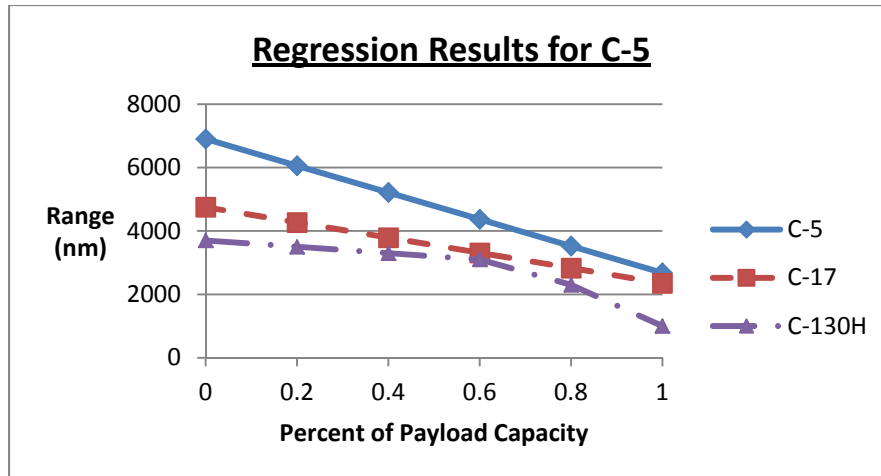


Figure 7. Payload capacity and range for C-5 airframe from linear regression

DRAP then calculates the maximum capacity (in pounds) of the route by determining what percentage of its payload the aircraft can carry on the longest leg. The number of routes generated is usually on the order of thousands. The algorithm and computations are performed in the Visual Basic Excel (VBA) program of the Microsoft Office suite.

### 3. Transportation Costs

DRAP calculates the costs of transporting the HA/DR material to the disaster nodes for each valid route in order for it to choose the most efficient routes that minimize costs and demand shortages. Transportation costs in DRAP are the sum of two components, the aircraft's fuel consumption and its operating costs.

Fuel consumption costs are derived by taking the distance of the entire route and multiplying it by the gallons per mile rate of the aircraft flying that route and the price of a gallon of fuel. DRAP's dashboard allows users to change the price of a gallon of fuel to reflect current prices.

An aircraft's operating cost is a static parameter input provided by the user on a cost per hour basis. DRAP is using 2012 operating costs that were provided by the J4 (Logistics) branch of USPACOM. To determine the operating cost for a route, DRAP takes the entire distance of the route and divides it by the aircraft's nominal cruising

speed to obtain the *duration* parameter, i.e., amount of hours required to fly that route. The hours are then multiplied by the aircraft's per hour operating cost to obtain the total operating cost for that route.

#### **4. Data Associated with Routes**

Once a route is created, we retain the aircraft type associated with the route, as well as the *cost* of the route, its *duration*, the *downtime* required for the particular aircraft flying that route, the percent of capacity to which the aircraft can be loaded, and the subsequent weight (*payload*) and volume (*cap*). The *downtime* parameter is an aggregated metric consisting of the total time, over all stops the aircraft makes on the route, that it takes to refuel the aircraft as well as the time it takes to onload or offload its cargo.

#### **5. GAMS Interface**

DRAP takes the generated routes and associated data and creates comma separated values data files that automatically populate the HA/DR Transportation Model discussed in section B of this chapter. We formulate HA/DR Transportation Model in the Generalized Algebraic Modeling System (GAMS) and solve using the integer linear program package CPLEX 12.4.00 (GAMS, 2012).

The solution to DRAP found by CPLEX optimizes route selection, commodity source, and aircraft payload to minimize transportation costs and demand shortages. The solution populates the "Results" spreadsheet in DRAP.

### **C. SCENARIO AND ANALYSIS**

We provide a scenario developed in coordination with USPACOM in order to show DRAP's value as an analysis tool as well as a planning and COA development tool.



## **1. Time Varying Scenario**

Let us suppose that a cyclone hits Malaysia and causes moderate damage due to flooding and winds. DoS has requested assistance from DoD and USPACOM is tasked with transporting HA/DR material to the affected state. Four commodities are required in the following amounts:

- 100,000 Humanitarian Daily Rations
- 100,000 Meals Ready To Eat
- 40,000 Blankets
- 6,000 Plastic Sheeting Rolls

Four destination airports in Malaysia are utilized (a/k/a demand nodes) and are specified here with their respective IATA codes:

- Sultan Abdul Halim (AOR)
- RMAF Butterworth (BWH)
- Kuching International (KCH)
- Kota Kinabalu International (BKI)

Supplies are sourced from five locations (a/k/a/ supply nodes) and are specified here with their respective IATA codes:

- San Joaquin, CA (SUU)
- Pearl Harbor, Hawaii (HNL)
- Guam (UAM)
- Busan, South Korea (BUS)
- Okinawa, Japan (OKA)

USTRANSCOM has allocated 11 air assets to the FHA operation, shown here by type and number as well as where they are based:

- 4 C-5s in San Joaquin, CA
- 2 C-17s in Pearl Harbor, HI
- 1 C-17 in Guam
- 2 C-130s in Busan, South Korea
- 2 C-130s in Okinawa, Japan

Commodities, demands nodes, supply nodes, and aircraft allocation are held constant while we vary the time horizon by 24, 48, and 72 hours.

## 2. Analysis for Time-Varying Scenarios

The results provided by DRAP for the three scenarios described above are shown in Table 3. As expected, as the time horizon increases from 24 to 72 hours, the demand shortages decrease but transportation costs rise. At 72 hours, we see that all demand commodities are delivered to the affected state. However, let us suppose that there is a budget restriction of \$10 million which would make the 72 hour course of action infeasible. Now we examine the 48 hour option which DRAP has identified as having a demand shortage of 52,461 pounds.

Time	Cost	Weight (lbs)	Pallets	Shortage (lbs)
24	\$3,429,640	1081660	144	107652
48	\$7,814,144	2265860	302	52461
72	\$12,447,500	3452652	460	0

Table 1. Disaster Relief Airlift Planner results for Malaysia cyclone scenario with time varying

By using the commodity penalization feature in DRAP, the planner is able to control which commodities will be shorted. This enables the decision maker to prioritize and further refine the decision space towards an operational plan to execute.

To find the optimal solution to the 72 hour scenario, DRAP generated 1301 routes to choose from and solved in 48 seconds with an optimality gap of under 5%. It generated 30,178 variables with 1,301 constraints. A screenshot of the top half of DRAP's results page is shown in Figure 8 and displays totals for cost, weight, pallets, and shortages, as well as aircraft usage by type and originating airport. It also provides information about each route and the number of times that route is flown.

	A	B	C	D	E	F	G	H	I	J	K	L
1	TOTALS: Transportation											
2	Cost	Weight	Pallets	Shortages								
3	12447500	3435000	458	0								
4												
5	TOTALS: Aircraft											
6	A/C Type	Airport	Routes flown									
7	C5	SUU	6									
8	C17	UAM	7									
9	C17	HNL	5									
10	C130	OKA	12									
11	C130	BUS	8									
12												
13	Route	Aircraft	Cost	Times flown	Weight	Pallets	Stops					
14	r1	C130	69108.44	1	36000	4.8 OKA	AOR					
15	r2	C130	48654.61	1	36000	4.8 OKA	BKI					
16	r4	C130	62787.35	10	360000	48 OKA	KCH					
17	r6	C130	66519.75	8	288000	38.4 BUS	BKI					
18	r117	C17	185966.9	6	803940	107.19 UAM	BKI					
19	r122	C17	229215.2	1	135000	18 UAM	KCH					
20	r247	C17	575300.9	5	512700	68.36 HNL	UAM	KCH				
21	r569	C5	1155596	5	1052800	140.37 SUU	HNL	UAM	AOR			
22	r592	C5	1170203	1	210560	28.07 SUU	HNL	UAM	BKI	KCH	AOR	
23												

Figure 8. Screenshot of top half of DRAP's Results Page

The bottom half of the Results page (see Figure 9) informs the planner of the source and destination for each commodity picked up and dropped off. In addition, here we would see more specific data for shortages by commodity and destination, if any existed.

	A	B	C	D	E	F	G	H	I
23									
24	PICKUP								
25	Airport	Commod	Amount						
26	OKA	BLKT	150						
27	OKA	MRE	19452.3						
28	BUS	MRE	13090.9						
29	UAM	BLKT	218.15						
30	UAM	HDR	48000						
31	UAM	MRE	12853						
32	UAM	PSHT	4105						
33	HNL	HDR	27000						
34	HNL	MRE	29603.8						
35	HNL	PSHT	395						
36	SUU	BLKT	2631.85						
37									
38	DROPOFF								
39	Airport	Commod	Amount						
40	AOR	BLKT	1000						
41	AOR	HDR	25000						
42	AOR	MRE	25000						
43	AOR	PSHT	1500						
44	BKI	BLKT	1000						
45	BKI	HDR	25000						
46	BKI	MRE	25000						
47	BKI	PSHT	1500						
48	KCH	BLKT	1000						
49	KCH	HDR	25000						
50	KCH	MRE	25000						
51	KCH	PSHT	1500						
52									
53	SHORTAGES								
54	(none)								

Figure 9. Screenshot of bottom half of DRAP's Results Page

### 3. Aircraft Allocation Varying Scenarios

Now let us suppose the same scenario as we have just examined only now we will hold time constant at a 48-hour time horizon (and commodities and demand nodes as before) and instead will vary aircraft allocation, i.e., how many of each type are based at the supply sources as shown in tables 2, 3, and 4. If we aggregate all aircraft types, we can say simply that Aircraft Allocation 1 has six air assets allocated to the mission, whereas Aircraft Allocation 2 has 11 (one more of each type in each location than Aircraft Allocation 1), and Aircraft Allocation 3 has 16 (again, one more of each type in each location than Aircraft Allocation 2).

Aircraft Base	Aircraft Allocation 1		
	C-5	C-17	C-130
SUU	2	-	-
HNL	-	1	-
UAM	-	1	-
BUS	-	-	1
OKA	-	-	1

Table 2. Aircraft Allocation 1 for Aircraft Allocation Varying Scenario

Aircraft Base	Aircraft Allocation 2		
	C-5	C-17	C-130
SUU	3	-	-
HNL	-	2	-
UAM	-	2	-
BUS	-	-	2
OKA	-	-	2

Table 3. Aircraft Allocation 2 for Aircraft Allocation Varying Scenario

Aircraft Base	Aircraft Allocation 3		
	C-5	C-17	C-130
SUU	4	-	-
HNL	-	3	-
UAM	-	3	-
BUS	-	-	3
OKA	-	-	3

Table 4. Aircraft Allocation 3 for Aircraft Allocation Varying Scenario

#### 4. Analysis for Aircraft Allocation Varying Scenario

We find the results for the three Aircraft Allocation Varying scenarios in Table 5 are much like those that we saw when we varied by time. As logic dictates, increases in the number of aircraft, increase the amount of commodities delivered and drive demand shortages to zero (see Aircraft Allocation 3). Of course, transportation costs also rise accordingly. As was the case in the time varying scenario, the decision maker may be

constrained by budget and so may be forced to prioritize commodities by using DRAP's commodity shortage penalization feature to control which ones will be delivered should a shortage exist.

Aircraft Configuration	Cost	Weight (lbs)	Pallets	Shortage (lbs)
1	\$3,908,540	1351660	180	94697
2	\$7,941,054	2717450	362	32139
3	\$9,907,277	3435000	458	0

Table 5. Disaster Relief Airlift Planner results for Malaysia cyclone scenario with aircraft allocation varying

## 5. Comparison of the Two Scenarios

The two disaster relief scenarios provided in this thesis represent alternative COAs that may eventually be developed into operational logistics plans. We have shown how DRAP can be used in time dominant or resource dominant variations and how the tool can deal with identified shortages in each.

What we can also do is compare transportation costs of each. Assume that the priority is to get all the required material delivered to the affected state regardless of time or aircraft allocation. We can compare the two configurations in each scenario that resulted in zero demand shortages. In the time varying scenario, it took 11 aircraft 72 hours at a cost of \$12,447,500 to achieve no shortages while in the aircraft allocation scenario it took 16 aircraft 48 hours at a cost of \$9,907,277 to achieve the same result. It is clear that the aircraft allocation is the dominant COA since all the disaster relief material is delivered faster (48 hours versus 72) and much cheaper (\$9.9 million versus \$12.4 million).

## 6. Scenario Complexity

The scenarios provided in this thesis are intentionally not very complicated. Their purpose is simply to demonstrate DRAP's use as a planning and analysis tool. In truth, DRAP can solve much more complicated scenarios, involving dozens of airports,

aircrafts, and commodities. Solutions of this size increases DRAP's computation time from the seconds it took to solve the scenarios provided to several minutes. This would save logistics planners hours if not days, assuming that a very complex scenario could be solved manually at all.

### **III. CONCLUSIONS AND RECOMMENDATIONS**

#### **A. SUMMARY**

The Disaster Relief Airlift Planner should be used as a decision support tool to plan airlift missions in support of FHA operations. It was created for use by USPACOM to support disaster relief in any country in its AOR (see Appendix for a complete list of countries). However, because the tool allows users to add any airport very simply, it can be used by other geographic combatant commands without modification of the program. Given commodity supply and demand data, and airport and aircraft usage, DRAP will identify which routes are optimal to airlift the most cargo at the least cost for any AOR.

The detail and efficiency of the model allows for the decision maker to explore multiple COAs very quickly. The scenarios provided above are just some examples of ways to accomplish this. DRAP may be varied not only by time horizon but also by budget allocation for transportation costs and resource allocation of type, number, and basing of aircraft. This tool allows the user to dynamically update data, rerun the model, and receive a solution in minutes.

Planners can use DARP to explore time-saving or cost saving dominant configurations in order to develop alternative COAs for the decision maker to examine. The tool is flexible enough to meet the varying issues of a given situation and robust enough to greatly aid in making an informed decision.

#### **B. RECOMMENDATIONS FOR FUTURE STUDY**

##### **1. Expanding DRAP**

DRAP is able to utilize any aircraft type provided the requisite information (payload, range, gallons per mile consumption, daily utilization rate, and downtime). Expansion of the model would include adding a commercial fleet of aircraft with their costs and capabilities, and then conducting analysis of time, transportation costs and demand shortages of using commercial versus military aircraft (or some combination of the two). This expansion could also assess the impact of limitations on military aircraft



usage (but not commercial) due to restrictive force protection conditions or diplomatic stipulations that arise due to some international event.

## **2. Modifying DRAP**

Because of the fast solution times, DRAP can be used to study cost and efficiency of resource allocation, i.e., airframes, to airports in preparation for a range of disaster scenarios. For example, it could be used for the Air Mobility Command at USTRANSCOM for this purpose, in much the same way ATEM has been used for aircraft fleet sizing analyses. As a standard practice, the AMC also plans fully loaded aircraft for its missions and uses aerial refueling as required if the route distance exceeds the aircraft's range. DRAP can be modified to allow routes with aerial refueling; this would require additional cost data for such routes (including refueling cost) and a mechanism to identify which flight legs are eligible for refueling.

## APPENDIX. COUNTRIES IN USPACOM AREA OF RESPONSIBILITY (AOR)

There are 36 countries<sup>[1]</sup> within the geographic boundaries of the USPACOM AOR.<sup>[2]</sup><sup>[3]</sup>

USPACOM has unique responsibilities regarding the Russian Federation.<sup>[4]</sup>

Australia	Laos	Philippines
Bangladesh	Malaysia	Samoa
Bhutan <sup>[5]</sup>	Maldives	Singapore
Brunei	Marshall Islands	Solomon Islands
Burma	Micronesia	South Korea
Cambodia	Mongolia	Sri Lanka
China <sup>[6]</sup>	Nauru	Thailand
Fiji	Nepal	Timor-Leste
India	New Zealand	Tonga
Indonesia	North Korea <sup>[5]</sup>	Tuvalu
Japan	Palau	Vanuatu
Kiribati	Papua New Guinea	Vietnam

<sup>[1]</sup> Per Department of State Fact Sheet, “independent state” refers to a people politically organized into a sovereign state with a definite territory recognized as independent by the U.S.

<sup>[2]</sup> Per 17 Dec 08 Unified Command Plan (UCP), “USPACOM general geographic AOR for the conduct of normal operations includes the Pacific Ocean from Antarctica at 092° W, north to 8° N, west to 112° W, northwest to 50° N/142° W, west to 170° E, north to 53° N, northeast to 65°30’ N/169° W, north to 90° N, the Arctic Ocean west of 169° W and east of 100° E; the People’s Republic of China, Mongolia, the Democratic People’s Republic of Korea, the Republic of Korea, Japan; the countries of Southeast Asia and the southern Asian landmass to the western border of India; the Indian Ocean east and south of the line from the India/Pakistan coastal border west to 068° E, and south along 068° E to Antarctica; Australia, New Zealand, Antarctica, and Hawaii.”

<sup>[3]</sup> USPACOM does not include “territories” or “possessions” on the list of “independent states” – even though such entities exist inside the confines of the AOR and represent sovereign land. Rationale: the governing country is either (1) already included in the list above (e.g., the Ashmore and Cartier Islands are a territory of Australia; Australia is on the list) or (2) outside AOR boundaries (e.g., Pitcairn Islands are a territory of the United Kingdom; United Kingdom is outside the AOR). IAW paragraph 9b of 17 Dec 08 UCP, USPACOM is “responsible for missions in and around territories and possessions within the AOR irrespective of the location of governing country. In such cases, USPACOM

will coordinate with the Combatant Commander whose AOR includes said governing country.”

[4] IAW paragraph 14d of the 17 December 2008 UCP, CDRUSPACOM has specific responsibilities in the Russian Federation: “In coordination with CDRUSEUCOM, in those areas of the Russian Federation east of 100° E, CDRUSPACOM conducts counterterrorism planning for all U.S. diplomatic missions; plans and, as appropriate, carries out force protection responsibilities, exercises, port visits, and similar operations; and conducts noncombatant evacuation operations.”

[5] No diplomatic relations with the U.S.

[6] Per Department of State Fact Sheet: “With the establishment of diplomatic relations with China on 1 Jan 79, the U.S. government recognized the People’s Republic of China as the sole legal government of China and acknowledged the Chinese position that there is only one China and that Taiwan is part of China.”

From [https://www.pacom.mil/web/site\\_pages/uspacom/regional%20map.shtml](https://www.pacom.mil/web/site_pages/uspacom/regional%20map.shtml)

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